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RESEARCH ON THE USE OF INDUCED POLARIZATION MEASUREMENTS TO STUDY THE MECHANICAL PROPERTIES OF UNCONSOLIDATED MATERIALS

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a precision exceeding that currently available for use in making induced polarization field surveys would be required to detect the effect. Because the sponsoring agency had no further interest in developing a method based on such sensitive measurements, field studies were not undertaken.

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RESEARCH ON THE USE OF INDUCED POLARIZATION
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Introduction

The problem of determining the engineering properties of the earth is often difficult and expensive to solve. A standard approach in engineering practice is to carry out an extensive drilling program once a site has been selected for construction. Samples and drill cores recovered from drill holes are removed to the laboratory for further tests. Often, if structural properties of the soil are of extreme importance, insitu tests of rock properties may be performed. Even with a high sampling density, the results of such testing are sometimes unsatisfactory. Testing is particularly difficult with unconsolidated materials whose properties change once holes have been drilled and samples taken.

The process of recovering samples for physical properties tests is expensive. It provides the best approach that can be used. However, if the problem is one of selecting a site rather than evaluating a site, the cost of carrying out such a study is prohibitive. In such cases, one must resort to less expensive but less definitive reconnaissance techniques for comparative evaluations of the engineering properties of the soil and subsoil. Such reconnaissance techniques are not yet well developed.

One inexpensive approach to determining variations in engineering characteristics of the soil and subsoil is by the measurement of electrical resistivity. In competent rocks, both the electrical resistivity and the rock strengths are

controlled primarily by the amount of jointing and fracturing. In such rocks, there is a loose but reasonable correlation between resistivity and rock strength. Thus, resistivity surveys can be used to locate those rocks with the highest resistivities and hence the most favorable properties for construction.

Loosely consolidated rocks and soils present a more difficult problem. In these, the electrical resistivity and the engineering properties are not closely related. Resistivity depends not only on the amount of pore space, but also on the amount of water and the salinity of the water that is present in the soil or rock. Thus, resistivity measurements cannot be used as a guide to locating areas with specific engineering properties.

Induced electrical polarization is also an electrical property of a rock, but one which has not been studied intensively insofar as its use in studying engineering parameters is concerned. Some experimental work has indicated that the induced polarization response of a rock is closely related to the clay content. Likewise, the bearing strength and plasticity of soils is often controlled by the clay content. Thus, the possibility exists that measurements of induced polarization may provide information on engineering properties that is not available from measurements of electrical resistivity.

The Air Force Cambridge Research Command undertook to support a project at the Colorado School of Mines to determine whether or not induced polarization measurements offer any promise for such an application. The program was to consist initially of a series of laboratory measurements of the induced polarization response of mixtures of clay and sand. This was to have been followed by field studies to determine the applicability of the laboratory results. The organization of the study and the results which were

obtained are described in the following sections.

Review of Previous Work

The measurement of induced electric polarization has been an accepted exploration tool in mining geophysics for several decades. The method has been described in some detail in several textbooks on geophysical exploration, including an early book edited by Wait (1959), one by Keller and Frischknecht (1967) and two very recent monographs by Sumner (1976) and by Bertin (1976). The main emphasis in each of these presentations is on the development of induced polarization in rocks which contain electronically conducting minerals. In such rocks, the induced polarization phenomenon is strongly developed.

As indicated on Figure 1, the source of the induced polarization effect lies in the chemical reactions which must take place when electrical current flows between an electrolytic solution in the pore spaces of a rock and an electronically semiconducting sulfide mineral blocking those pore spaces. In order to transfer charge from the electrolyte to the semiconductor in the reverse sense it is necessary for oxidation or reduction to take place at the interface. As with all other chemical reactions oxidation and reduction are rate controlled by the concentrations of reactants that build up as current tends to flow through the interface. Prolonged current flow will lead to the development of a concentration of ions near the interface. This concentration accelerates the chemical reaction which permits charge to be transferred across the interface. It also represents a storage of charge at the interface, or "polarization".

The effects of this polarization can be recognized if the flow of direct current through a rock containing such structures

is abruptly interrupted. With the cessation of current flow, the accumulation of ions at the interface is no longer supported by a supply of energy. The ions will diffuse slowly back to a neutral position giving rise to a transient current decay after the external field has been removed. When the external field is removed, the voltage drop across the rock will decrease suddenly initial transient voltage rather than to zero. The voltage will then decay slowly with time with a measurable level persisting for many seconds or many minutes. The initial level to which the voltage drops is controlled by the number of interfaces present in the rock. Typically it is of the order of twice the volume fraction of sulfide mineral in the rock. Ideally, it would be zero or close to zero for rocks with no sulfide minerals present.

This phenomenon of induced electrical polarization in rocks has been recognized for many decades, with the first description in the literature being that of Schlumberger (1920). Although this early work of Schlumberger was valid, further use of induced polarization in geophysical exploration proceeded very slowly. It was not until the later 1940's and early 1950's that the method came into widespread use in mineral prospecting. It was only then that it was found that induced polarization is a general characteristic of rocks whether or not they include electronically conducting minerals. The term "induced electric polarization" is used qualitatively to describe the phenomenon shown in Figures 1 and 2. A variety of quantitative measures of induced polarization have come into use in geophysical circles. For example, one simple measure of induced polarization level is the ratio of the initial transient voltage shown on Figure 1 to the steady state voltage. This quantity is normally measured in millivolts per volt. Often, it may not be convenient instrumentally to record a transient with equipment having a rapid enough response to

detect the initial voltage of a transient accurately. In this case, it is customary to measure the integral of the transient voltage curve as a function of time, and normalize the resulting value with respect to the steady state voltage. The usual units of measurement are millivolt seconds for the integral and volts for the steady state voltage, or milliseconds.

Still another way to measure the effects of induced polarization is by determining the voltage drop across a sample using two like currents at different frequencies. At the higher of the two frequencies the amount of ion concentration that takes place in the pore space is less than at the lower frequencies. Thus, at the higher frequency, there will be less counter-potential built up by the ion concentrations, and for a given current, the voltage drop across the sample will be lower. This behavior manifests itself as an apparent change in the electrical resistivity of the sample with frequency. In geophysical circles, this dispersion of resistivity with frequency is measured as a percentage per decade change in frequency or pfe (percentage frequency effect). Sometimes this percentage frequency effect is divided by the resistivity, then multiplied by a constant - 50,000 - and called the "metal factor".

As pointed out by Hartshorn (1926), the induced polarization effect can be separated into a part which is strictly in phase with the applied voltage, and another part which is strictly out of phase with the applied voltage. These two phenomena can be considered to be a change in the dielectric constant of the material with frequency and a change in the electrical resistivity with frequency. The two changes cannot be independent of each other because they comprise a realizable system in a mathematical sense. Therefore, if the change in one of the parameters, either resistivity or dielectric constant, is known, the change in the

other can be computed from an appropriate form of the Fourier transform. There is an obvious advantage in using dielectric constant or electrical resistivity to specify the effects of induced polarization, in that these are generally accepted definitions and the units are well known. It must be pointed out that such usage is not yet prevalent in geophysical circles.

Perhaps the first geophysicist to recognize that induced polarization exists in normal rocks was Evjen (1948) who attempted to use electromagnetic coupling to measure the electrical properties of the earth. He measured the transient fields that exist in the earth when a magnetic field is abruptly terminated. The change in magnetic field should be accompanied by transient electric currents in the ground whose duration is determined by the electrical conductivity. These transients are relatively short lived compared to induced polarization effects. Therefore, Evjen recognized that some phenomenon that he had not anticipated was taking place. He postulated that the dielectric constant of the earth would need to be of the order of 10^8 to 10^{11} to explain his results. Unfortunately, he dismissed this as being somewhat of a physical absurdity.

Farnham (1949) carried out an extensive field study with induced polarization measurements, primarily in Maryland. He noted that the induced polarization effect can be produced in a large number of rock types. He also pointed out that some other cause for induced polarization effect than the presence of metallic conductors in the ground should be sought. Moreover, he pointed out that induced polarization effects are not safe criterion on which to base the prediction of occurrence of mineral deposits. While all of these conclusions have subsequently been verified by other investigators, he went on to point out that no utilitarian value of the induced polarization effect as such has been established in his work. Farnham also spent considerable effort in attempting to characterize transient decay of voltage in rocks.

He suggested that a formula which fitted the voltage decay of the induced polarization effect well was

$$E = kE_0 e^{-Nt}$$

where E_0 is the initial voltage observed during transient decay, T is the time following the beginning of the transient decay, and k and N are empirical constants required to fit the data. He also observed that N has a value of approximately 0.3. A set of Farnham's data fit with a line having a slope T^3 is shown in Figure 3.

This phenomenon of a nonelectronic induced polarization effect or "background" effect as it has come to be known was studied further by Keller and Licastro (1956, 1959). They chose to use the method of measuring dielectric constant and electrical conductivity separately as electrically orthogonal parameters describing the response of a material to an external electric field. The materials with which they worked were partially water saturated sandstones and siltstones. Their measurements indicated that the rocks with a relatively high water content the eletrical conductivity varied with frequency over the low frequency range, and that dielectric constant varied radically. Some of their values for dielectric constant were as high as 10^8 or 10^9 at frequencies below 100 hertz. These numbers were comparable to those arrived at by speculation by Evjen (1948) and dismissed.

Normally, dielectric constants are rarely larger than 100, when they represent the effects of electric polarization in materials on an electronic or atomic scale. However, very large values for dielectric constants have been recorded for unusual materials. For example, Fricke (1925, 1926) reported values as large as 10^3 to 10^5 for some biological cell suspensions. Fricke and Curtis (1935) reported high values for kaolin-gelatin

suspensions, Koops (1951), for artificially prepared ferrites, Von Hippel (1954) for bottom round steak, Dunlap and Makower (1945) for dehydrated carrots and Smith-Rose (1934) and Tarkhov (1948) for rocks and other earth materials.

Keller and Licastro (ibid) proposed a microscopic scale phenomenon of ion concentration to explain the polarization represented by these high values of dielectric constant. In their model, as shown in Figure 4, polarization was postulated to take place in small diameter pores partially blocked by clay minerals. These clay minerals exhibit the phenomenon of electrolysis to the extent that some ions in so-called exchangeable positions within the crystal lattice of the clay mineral may go into solution in the pore-water, leaving the clay mineral strongly negatively charged. This negatively charged clay particle then presents an electrostatic barrier to the migration of cations through the pore structure. The accumulation of ions at such a barrier during current flow will be precisely the same phenomenon as described previously for the collection of ions at a sulfide-electrolyte interface. They also speculated that the efficacy of such a membrane effect would depend strongly upon the amount of clay mineral present, the cation exchange properties of the clay mineral, the pore sizes, and the salinity of the pore fluid. Marshall and others (1957), Nourbehecht (1963) and Marshall and Madden (1959) also carried out extensive research on the nature of background effects in induced polarization surveys at the Massachusetts Institute of Technology. They likewise discovered that the causes of induced electrical polarization include not only the reactions at sulfide-electrolyte interfaces, but also effects associated with other modes for storage of energy in the rock. They considered the possibility that electro-osmotic effects, thermoelectric effects and ion diffusion effects could

serve to give rise to induced polarization. After careful study, they concluded that diffusion in a porous membrane is the only background effect likely to be important. In their model, they consider that the mobility of cations will vary from zone to zone in the pore structure as indicated in Figure 5, which is reproduced from Figure 9 of Marshall and Madden (1959). As may be seen, this model is equivalent to that proposed by Keller and Licastro (1957).

The phenomenology of current flow through porous membranes has been a subject of considerable research outside of the realm of geophysics (Sollner, 1945, and Dukan, 1962). Such research has shown that it is not necessary to have electrostatic barriers to produce variations in the mobility of ions within a membrane. Rather, variations in mobility can be present merely because of the absorption of water on the solid surfaces surrounding the pore structure. When water is absorbed, its viscosity is markedly increased over that in the free state, and therefore, the mobility of ions moving through it is reduced. If the diameter of pore spaces becomes comparable to the thickness of an absorbed layer of water on the pore walls, the mobility of ions may be reduced as much as a thousandfold. If a pore structure varies in diameter, ions will move rapidly through the wider parts of the pore structure and more slowly through the thinner parts. Ion accumulations will take place then at the boundaries between these zones with differing ion mobilities. Thus, induced polarization effects will be expected to take place even in those rocks which are free of clay minerals, providing some of the pore structures are comparable in size to the dimensions of an absorbed layer of water on quartz.

Still another model for the induced polarization effect in nonmineralized rocks has been proposed by Dakhnov (1962). In

Dakhnov's model, the polarization takes place in the absorbed layer of water around each mineral grain in the rock. The absorption of water on a solid surface organizes the water molecules in a consistent manner so that their dipole moments are lined up. When an external electric field is applied Dakhnov postulates that the absorbed layer is elastically distorted because of its dipole moment. When the external electric field is removed, the water molecules will gradually return to their undeformed state. Since they are polarized, this motion of the water molecules will constitute a transient current. In Dakhnov's model, the amount of polarization will be closely related to the specific surface area of a rock, the specific surface area is the ratio of grain surface to the volume of the pore space. Fluid permeability is also closely related to specific surface, and thus, Dakhnov speculated that induced polarization measurements would be effective in measuring the fluid permeability of rocks.

Dakhnov's hypothesis about the relationship between induced polarization and specific surface of a rock was supported by very extensive laboratory research (See, for example, Dakhnov and Dobrinin, 1959; Dakhnov and Dolina, 1959). They have presented empirical correlations between induced polarization in sandstones and siltstones with permeability and with specific surface area (see Figure 6). Apparently, such correlations were used with moderate success in several areas in the Soviet Union to estimate fluid permeabilities in oil-producing horizons. In a more recent paper describing attempts to use induced polarization logs for the same purpose in other producing areas, Komarov and Kotov (1964) found that the correlations shown in Figure 6 are not generally applicable (See Figure 7). The correlation or lack of it, between

permeability and induced polarization in these cases led to a discrediting of the method. It would appear that Dakhnov's hypothesis about elastic rebound of absorbed water may not be a valid explanation of the induced polarization effect.

Henkel and Collins (1961) carried out a series of experiments to attempt to identify the physical mechanism involved in the background effect. They considered two postulates: in the first, induced polarization would occur like electrical dipole polarization on the surface of clayey particles, and in the second, the induced polarization would take place as a concentration of ions in solution next to the clay particle. They concluded that the second description of the effect was more successful in simulating observed data than the first model in two ways: (1) the second model provided a time dependence that was more nearly consistent with experimentally observed decay voltages; and (2) the second model led to equations involving the resistivity of the saturating solution which were also more consistent with experiments. Keevil and Ward (1962) carried out research to analyze the then existing data on induced polarization, to design equipment to measure induced polarization under natural conditions, and to study the effect of electrolyte activity and other variables on induced polarization. Among many conclusions related to induced polarization in metal bearing rocks, they point out that changes in electrolyte activity greatly influence induced polarization. The induced polarization associated with membrane effects decreases with increasing activity of the electrolyte in the pore spaces. They also point out that the amount of clay seems to have little effect on the induced polarization of sandstone saturated with saline water. In all cases the induced polarization for such rocks is low or negligible. Keller (1960) found that induced polarization decreased with the increasing salinity of the pore fluid, but not strongly.

Anderson and Keller (1964) describe a series of measurements made on clay bearing sandstones in which they attempted to calculate the induced polarization effect from the cation exchange capacity of the rock. They obtained a correlation that supported the concept that a membrane effect is an important part of the total induced polarization in the rocks.

With the growth of the concept that induced polarization background effect was a measure of the clay content and grain size of sedimentary rocks, a number of investigators investigated the application of the induced polarization method to ground water studies. Among the first of these were Vacquier and his colleagues (1957). Among their studies, they included laboratory measurements of induced polarization effect made on synthetic samples consisting of quartz sand mixed with a few percent of clay mineral and saturated with a weakly saline solution. They found that in order to obtain measurable induced polarizations in these unconsolidated mixtures, it was necessary to let the mixture dry from a wet state and then be resaturated. Apparently the drying permitted the clay particles to coat the sand in such a way that the induced polarization effect was enhanced. With such a mixture they obtained very small induced polarization effects in which the initial voltage of the transient decay was less than 1/2 percent of the steady state voltage. A set of decay curves taken from their paper is shown in Figure 8.

More recently, the use of induced polarization to study the water collecting properties of rocks has been reviewed by Mohamed (1970). He quotes the earlier work of Fredricksberg and Sidarova (1962) who also postulated the concept of varying ion mobility in a membrane as a mechanism for the generation of induced polarization in granular rocks. He carried out a number of laboratory experiments which also tended to confirm the membrane mode for induced polarization. Similar results have also been reported by Belluigi (1956).

Ogilvy and Kuzmina (1972) have recently reviewed work done on the use of induced polarization in hydrogeology and engineering geology. They point out that because of the complicated nature of induced polarization in ion conducting media, the subject still has not been adequately studied. However, they conclude that the effect is evidently associated with diffusion processes occurring between narrow and wide capillaries and controlled by membrane effects when clay minerals are present. They indicate that laboratory studies have established empirical relationships between induced polarizations of sand and clay mixtures with particle size distributions, porosity, moisture content and salinity. They suggest that induced polarization measurements can be used to characterize the nature of sand-clay sediments.

Shuey and Johnson (1973) extended the work of Keller (1959) with more mathematical rigor. Also, in a recent paper, Zonge and Wynn (1975) point out the advantage of measuring induced polarization in terms of real and imaginary components of impedance. These are in turn the basis for calculating induced polarization phenomena as values for dielectric constant and electrical conductivity. Their papers show promise that applied geophysicists will ultimately make use of standardized physical definitions in characterizing induced polarization.

In summary, geophysical investigators have come to recognize that the induced polarization effect takes place in rocks without electronically conducting minerals, as well as in mineralized rocks. A variety of mechanisms to explain this phenomenon have been promulgated, but the experimental evidence in hand today indicates that the background effect is caused by variations in ion mobility in small dimension pore structures. Clay minerals play an important role in causing mobility to change because they exert strong electrostatic barriers to cation flow. It is to be expected that induced polarization will depend to some extent on the amount of clay mineral present, but it will also

depend on the type of clay mineral, on the salinity of the pore fluid, and on the size distribution of pore spaces. The experience of Vacquier (1957) indicates that in unconsolidated clay-sand mixtures, the induced polarization effect may be smaller than that which can be measured with conventional equipment.

Laboratory Studies

In view of the very small amplitudes of induced polarization which may be present in clay-sand mixtures, laboratory measurements must be made with great care. A measurement cell similar to that used by Mayper (1959) was fabricated for the measurements. The cell, as shown in Figure 9, consists of a central reservoir in which the clay mixture under test is contained. No metal electrodes are used in this reservoir for fear that the polarization associated with their interface to the electrolyte will be larger than the effect to be measured in the clay-sand mixture. Current is provided from two electrodes contained in auxilliary reservoirs connected to the main reservoir only through capillary salt bridges. The voltage drop within the sample in the central reservoir is detected with a pair of calomel electrodes.

Because of the relatively high AC noise level in the laboratory, it was found necessary to place the induced polarization measuring cell inside a mumetal chamber to shield it. The switches and current supply for the polarizing current, and battery operated DC amplifiers for the signal were also contained within the mumetal (?) chamber. The preamplified voltages from the test cell were recorded on a high speed galvanometric recorder. This recorder had a basic sensitivity of 1 microvolt per millimeter, a galvanometer frequency of 50 hertz and a charg speed of 50 millimeters per second. The recording system would permit faithful recording

of the transient response even at the initial onset of the transient voltage. Samples were made with sized sand mixed with varying amounts of kaolin (?) or montmorillonite clay.

In a series of laboratory measurements, no induced polarization effects above 0.1 percent of the steady state voltage could be measured. It was concluded from these studies that a recording system with a greater dynamic range would be needed to detect and measure the induced polarization effects in these mixtures. It was proposed to the sponsoring agency that peripheral equipment in the form of a digital to analog converter be purchased to permit the induced polarization signal to be entered into a DEC PDP-11 computer for signal enhancing. The analog-to-digital converter provided a 12 bit resolution, corresponding to a dynamic range of 76 DB. This would have permitted detection of induced polarizations as small as 2 parts in 10,000 of the steady state voltage.

Because of a change in needs of the sponsoring agency, authorization to proceed with these measurements was not forthcoming. As a consequence, the research program has been terminated with the measurements as described.

Summary of Results

Both the experience of previous researchers and our present laboratory measurements indicate that in loosely consolidated materials, induced polarization depends on the type and amount of clay present as well as on other physical properties. The level of induced polarization is very low compared to that in consolidated rocks or in mineralized rocks. It appears unlikely that these levels of induced polarization can be measured with conventional equipment which has as its threshold of resolution

the detection of induced polarization levels of 1 or 2 percent. It may be that with advanced signal processing, lower levels of induced polarization can be measured both in the laboratory and in the field. Whether or not this will provide useful results in providing information for engineering applications remains an open question.

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